

# FARADAY ROTATION DENSITOMETRY FOR LHD

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## Abstract

A polarimeter which measures the Faraday rotation of a CO<sub>2</sub> laser beam in LHD plasmas is being developed to back up interferometry. An accurate measure of the rotation angle would enable us to monitor the electron density in LHD, where confining magnetic field can be computed at least for low plasma pressure. Frequency-shifted heterodyne techniques are applied to a tangential optical layout on the midplane. Preliminary tests without plasma indicate that the phase resolution at a beat frequency of 100 kHz or higher drops below 0.1 deg. with a time resolution of 10 ms.

## 1. Introduction

The electron density is one of the most important parameters which represents the confinement performance. Therefore, the measurement of it in nuclear fusion devices requires both the accuracy and the reliability. Interferometry is a widely used method for the electron density measurements. However, it has a problem with respect to reliability because of "fringe jump".

The Faraday rotation angle in a magnetically confined plasma gives the line integral of the electron density times the magnetic field component parallel to the probing beam. In helical devices such as Large Helical Device (LHD), the internal magnetic field in low  $\beta$  plasmas is almost determined by the currents in the external magnetic field coils. Therefore, the electron density can be monitored by measuring the Faraday rotation angle (polarimetry). By this method, real-time measurement is possible and suitable for long-time discharges of LHD. In addition, it also has an advantage over interferometry of immunity against vibrations of devices along the beam path. Due to these reasons, it is expected as a substitution or backup for interferometry. However, the Faraday rotation angle is generally so small that the improvement of the angular resolution is required when a short-wavelength beam is adopted to avoid refraction effects.

In this article, a preliminary study and tests for designing the Faraday rotation densitometer for LHD are described.

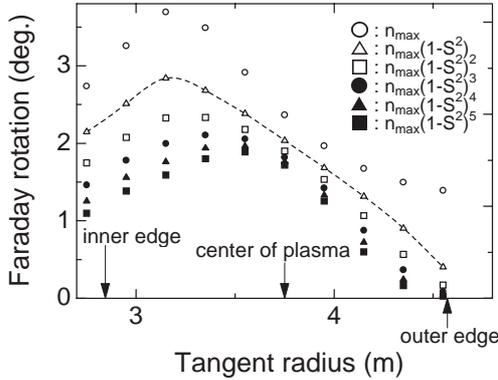
## 2. Determination of probing laser

The approximate expression for the Faraday rotation angle  $\alpha$  in magnetically confined plasmas is as follows:

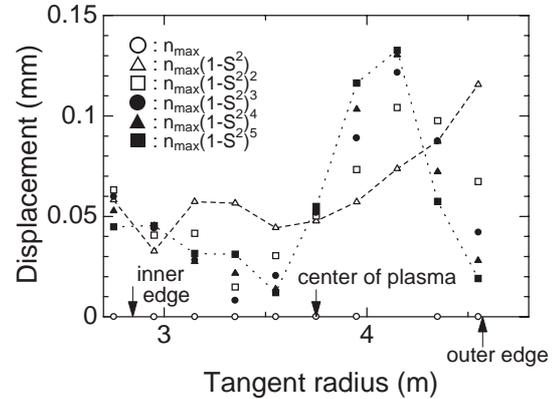
$$\alpha = 2.62 \times 10^{-13} \lambda^2 \int n_e B_{\parallel} dl \quad [\text{rad}] \quad (1)$$

where  $\lambda$  is the wavelength of the probing beam,  $n_e$  is the electron density and  $B_{\parallel}$  is the magnetic field component parallel to the probing beam. Eq. (1) means that the Faraday rotation angle is proportional to the square of the wavelength. Although large rotation is desirable for measurement, the longer wavelength is used, the larger refraction in plasma makes the measurement difficult. Therefore, the determination of the wavelength of probing beam is very important for good measurement.

We made numerical calculations where the three-dimensional helical configuration of LHD is taken into account and estimated both the Faraday rotation angle and the deviation by refraction in plasma for different wavelengths of the probing beam. From this result, we choose a CO<sub>2</sub> laser as the beam source since the wavelength (10.6  $\mu\text{m}$ ) of it is nearly optimum for LHD plasmas in respect that the Faraday rotation angle is measurable ( $\sim 2$  degrees through the plasma center) and that the refraction in plasma is sufficiently small ( $\leq 0.15$  mm). Figures 1 and 2 are examples of the results for CO<sub>2</sub> laser (10.6  $\mu\text{m}$ ) and shows the spatial profiles of the Faraday rotation angle and the beam displacement by the refraction in LHD plasma under the condition of a central magnetic field  $B_t(0) = 3$  T and several electron density profiles  $n_e = n_{\text{max}}(1 - S)^i$  where  $i$  is an integer,  $n_{\text{max}}$  the central electron density ( $1 \times 10^{20} \text{ m}^{-3}$ ) and  $S$  the normalized flux radius, respectively.



**Figure 1.** Faraday rotation angle as a function of tangent radius in an LHD plasma for different electron density profiles.

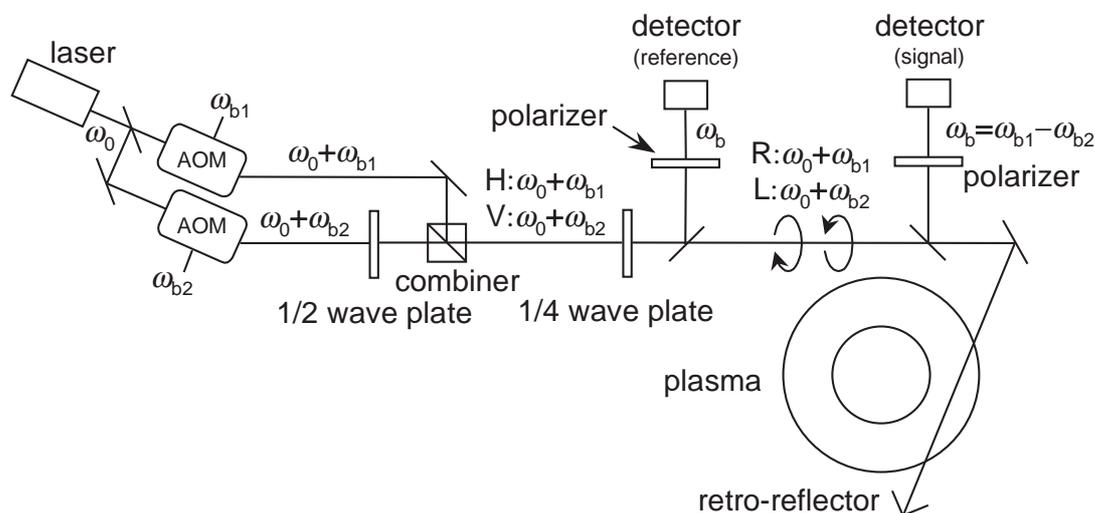


**Figure 2.** Beam displacement due to refraction in an LHD plasma.

Generally, this type of line-integrated measurement requires many chords to evaluate local quantities. However, it is not always realistic due to the limitation on diagnostic ports or optical components. If we prepare two chords (for example, one is through the center of plasma and the other more inner chord), the Faraday rotation measurements could give some information on the electron density profile from Fig. 1.

### 3. Optical layout

The optical layout under study similar to one proposed by Jobes [1, 2] is shown in Fig. 3. In order to improve the resolution of measurements, we adopted the frequency-shifted heterodyne method [3].



**Figure 3.** Schematic optical layout.

Firstly, the beam from the  $\text{CO}_2$  laser beam is split by a half mirror into two and their frequencies are slightly and differently shifted by two acousto-optic modulators (AOM). After the polarization plane of one of the two beams is rotated by  $90^\circ$  with a half wave plate, both beams are combined together again. Then, a quarter wave plate makes them two counter-rotating circularly polarized beams at different shifted frequencies. They pass through the plasma tangentially on the equatorial plane and return to the coming path at a retro-reflector in the vacuum vessel. This makes the beam path twice and correspondingly doubles the Faraday rotation angle with only one required diagnostic port. Finally, the beams are square-law detected with the reference and signal detectors. As a result, four times the Faraday rotation angle is detected. In practice, the total Faraday rotation angle includes that through the vacuum window. However, since the helical magnetic field produced by superconducting magnets is maintained almost constant in LHD and the vertical field makes no influence on the Faraday effect of the vacuum window, it will be just an offset and extracted easily from the acquired data.

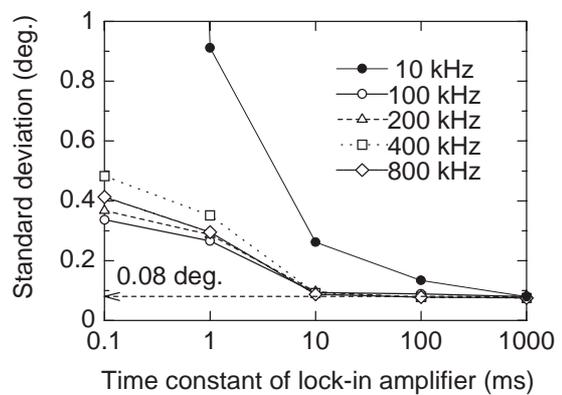
In this layout, the Faraday rotation angle is detected as a change in the phase between the signals from reference and signal detectors at the frequency which is the difference (beat) of the shifted frequencies, which is under testing with a half wave plate mounted in a programmable rotator with an accuracy of  $0.01^\circ$  to simulate the Faraday effect in a plasma. As shown in Fig. 3, the beam paths of two counter-rotating circularly polarized beams are basically the same. Therefore, this method doesn't suffer from the vibrations of optical components unlike interferometry and brings a great advantage for construction of the optical system.

## 4. Tests and results

As described in the previous section, the Faraday rotation angle corresponds to the phase difference between the signals from reference and signal detectors. Therefore, the tests for checking the accuracy of phase-difference measurements were made in advance.

In the test, we arranged the same optical parts as in Fig. 3 on a bench except that no plasma was included and the beam path was short compared to that for LHD. The output power of the CO<sub>2</sub> laser (MPB Technologies Inc., Model GN-802GES) was about 6 W. We used a lock-in amplifier (EG&G Princeton Applied Research Model 5302) and measured the standard deviations of the phase output, which determine the angular resolutions, varying the time constant of the lock-in amplifier and the beat frequency.

The results are summarized in Fig. 4. We got the standard deviation of  $\pm 0.08$  deg. under the condition for the beat frequency of not lower than 100 kHz and time constant of not shorter than 10 ms. This means that the measurement with an angular resolution of  $\leq 0.1$  deg. and a time resolution of  $\sim 10$  ms is possible at worst. However, this is not enough for our goal of accuracy, which is the measurement of three significant digits, that is, angular resolution on the order of 0.01 deg. In this test, the angular resolution appeared to be determined by not optical layout but the performance of the lock-in amplifier. We intend to improve the angular resolution by some digital signal processing.



**Figure 4.** Standard deviation of phase output as a function of the time constant of lock-in amplifier for different beat frequencies.

## 5. Conclusions

A preliminary study and tests for designing Faraday rotation densitometer for LHD was described. It was shown that CO<sub>2</sub> laser is nearly optimum for LHD with respect to both measurable Faraday rotation angle and sufficiently small refraction. The optical layout based on the frequency-shifted heterodyne method was considered to raise the resolution of the Faraday rotation angle. We got a prospect that the measurement with an angular resolution of  $\leq 0.1$  deg. and a time resolution of  $\sim 10$  ms is possible at worst.

## References

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